Modeling the Impact of Escaped Farmed Salmon on Wild Salmon Population

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1 Abstract

Each year thousands of farmed salmon escape fish farms which affects the wild salmon population both directly and indirectly. Escaped salmons has impacted the fitness and productivity of the wild salmon population. Our model aims at simulating the impact of escaped farmed salmon on the wild salmon population to investigate how the wild population's fitness and productivity is impacted based on the intrusion level of escaped salmons and the size of the wild population. Our model considers three varieties of salmons, namely, escaped farmed salmons, wild salmons and hybrid salmons which are introduced when escaped farmed salmons reproduce with wild salmons. We observed the population of salmons over four generations (roughly 24 years) and found that at low intrusion rate, farmed salmon find it dfficult to establish themselves but at higher intrusion rate, they easily overtake the salmon population, especially when the wild population is relatively small. In large fish schools, we found that the hybrid population takes.

2 Background

Escaped farmed salmon has always been a worry to wildlife authorities. As global consumption of salmon keeps on increasing, there is more pressure to produce more salmons. When thousands of atlantic salmon escaped a fish farm in August 2017, the situation was highlighted as an 'environmental nightmare' (npr, 2017). Studies such as that carried out by Naylor et al.(2005) have found risks of damage to the wild population of salmons when exotic pathogens are introduced and when farmed salmons are in great quantity. Ferguson et al.(2007) found that escaped salmons had both direct and indirect genetic effects on wild salmons which caused a loss of fitness. These effects were cumulative over generations if escaped salmons continued to merge with the wild population.

Hindar et al.(2006) used experimentals results to model the genetic and ecological effects of salmon farming on wild salmon over ten generations. They found that when the intrusion rate was small, there was a low probability that farmed offspring would dominate the population but found that at high intrusion rate, farmed offsprings and hybrids make up a large proportion of the salmon population. They focused on the effects of interbreeding and differential survival. They presented their results as porportions of the different varieties of salmons of the total population. They ignored location variation and used empirical results of survival and spawning rates to create their model. They set their intrusion rate at 20%. They considered the impact of seasons in calibrating the survival and spawning rates of the different varieties of salmons. They also analyzed their models by varrying intrusion and spawning success. McGinnity et al.(2003) carried out a two-generation experiment to assess the estimated lifetime successes, relative to wild natives, of farmed salmons and hybrids. They found that the offspring of farmed and hybrid salmons had reduced survival rates as compared to those of wild salmons. Their results showed that the interaction of wild salmons with farmed ones produced offspring with lower fitness and if more escaped salmons kept joining the population, there could be an extinction if the population is vulnerable. The experiment was undertaken in the Burrishoole system in western Ireland and consisted of a freshwater lake. For their research they sampled salmons by examining 3 cohorts from 1994, 1994, and 1999 but excluded the returning adults of 1998 which they identified from microtags.

Taking into consideration experimental results of fitness and productivity on salmon populations with interaction of escaped farmed salmons, the purpose of this study was to model the impact of escaped farmed salmon on wild salmon population, both in terms of population size and age distribution which indicates survival success. We investigated the effects of intrusion rate of escaped salmons and the size of the existing wild population on the population make up of salmons over four generations and focused on the proportion of wild salmons.

3 Method

We have followed the ODD (Overview Design Details) protocol designed by Grimm et al.(2006) to describe our model.

3.1 Purpose

The purpose of this model is to assess the impact on wild salmon population given the rate of intrusion of escaped farmed salmon and the initial size of the wild salmon population. In particular, we are interested in comparing the proportion of wild salmons, escaped farmed salmons and hybrids over a four-generation period and the age distribution of each variety which would indicate how successful the different varieties have been at survival given the change in the population structure.

3.2 State variables and scales

The models consists of three varieties of salmons, namely, wild salmons, escaped farmed salmons, and hybrids. We have set the lifespan of a salmon to be between 0-6 years. We will run our model to cover a four-generation period or roughly 24 years. The tables below describe our parameters and variables.

Table 1: Parameter Description

Parameters	Description	Scale/Metrics
INTRUSION RATE	Number of escaped salmons as a percentage of wild population	Percent
NUMBER OF WILDS	Population of wild salmons at initialization	Number of wild salmons
r1	Measured in terms of body length of salmon	fixed at 9.4
r2	Measured in terms of body length of salmon	fixed at 10.6
r3	Measured in terms of body length of salmon	fixed at 35.8
pay-attention-to	Number of nearby fish	fixed at 4
visionangle	as given	fixed at 300

Table 2: Variable Description

Variables	Description	Scale/Metrics
VARIETY	The variety of salmons can be wild, farmed (escaped), or hybrid	0: wild 1: farmed 2: hybrid
SEX	Sex of salmon	0: Male 1: Female
AGE	Age of salmon	(0-6)
CLOCK	shows how many ticks have elapsed.	1 tick = 1 year 6 ticks = 1 generation

3.3 Process overview and scheduling

The model starts with fixing the intrusion rate and initial wild salmon population. Each tick represents one year. For the intrusion rule, each year a number of escaped wild salmon enter the school as a proportion of total wild population as specified by the intrusion rate. Schooling rules have been left as the default values of the basic fish schooling model programmed by Professor T. Leise for Math 140. Escaped farmed salmons will follow the schooling rules on joining the wild population. For the spawning rules, the female salmon will reproduce with their eligible nearest male neighbor given a probability based on their age, sex and variety. If two salmons do reproduce, they die after spawning, thereby generating a new life cycle. The interaction between a wild salmon and an escaped farmed salmon generates a hybrid population. Survival at each stage depends on a given probability based on age, variety, and sex. Salmons die when they reach the maximum age, which we set at 6. We assess the salmon population after 24 ticks which represent a four-generation period.

3.4 Design concepts

Emergence: Population dynamics arise from the behavior of the agents but an agent's life cycle and behavior follows the empirical rules, such as survival and spawning rates as probabilities. Therefore, fitness is not modeled explicitly, but are accounted for in the rules.

Sensing: Each agent knows their own sex, age, and variety and the sex and maturity of the other agents so that spawning and survival probabilities apply. The agents also knows the distance from their neighbors so that the schooling rules apply.

Adaptation: Wild salmons have a better chance of laying eggs when they reproduce among themselves. Salmons creating hybrids have a greater number of offspring but these offspring tend to have a relatively lower survival chance, thereby decreasing the fitness of the new generation.

Fitness: Fitness is not modeled explicitly but is accounted for in the empirical rules, such as survival and spawning rates as probabilities. Fitness is thus explicitly measured by the probabilities that agents survive at each stage of their life cycle and spawning success.

Prediction: In estimating future consequences of their decisions, how do individuals predict the future conditions they will experience?

Interaction: Females at reproductive age try to reproduce with the closest male at reproductive age, regardless of variety. After spawning, the pair dies. If they don't reproduce they move on to the next eligible agent and try to reproduce.

Stochasticity: All survival and spawning rates are interpreted as probabilities. This was done to mimic empirical results so that the model is as realistic as possible.

Observation: For model analysis, we measure proportion of each variety over time. We also look at the age and sex distribution for each variety.

Collectives: Since we are modeling salmon population, the agents are modeled in schools as salmons tend to form schools before they hit the ocean at the near end of their life cycle. Escaped farmed agents will also join the schools.

3.5 Initialization

At the start of the simulation run, the parameters intrusion-rate and wild-population are set. Based on the wild-population number, the wild population school is generated at a random location. The number of escaped farmed agents are also generated based on the intrusion rate and wild population number. The wild agents are yellow in color while the escaped farmed ones are in pink. There is no hybrid (green-colored) agents at initialization. The sex, size and age of the agents are randomly attributed. The size of the schools are set at r1 = 9.4 units, r2 = 10.6 units and r3 = 35.8 units. The mean speed of the wild salmons is set at 1.2 body length / sec while that of the escaped farmed salmons is set at 2 body length / sec. Each agent will pay attention to its four nearest agents. Wild salmons don't head to any particular direction while escaped ones are heading towards the right and then integrate the wild population.

3.6 Input

The number of escaped farmed salmons that are added to our model is influenced by the current level of the wild population at any given time. This configuration ensures the possibility of assessing the impact of intrusion rate under different scenarios. We decided to analyze the population over a four-generation period to enable analyzing the population change over a considerable period of time. Once the initial wild population and intrusion rate are set, the model will work based on the stochasticity and empirical rules pre-defined.

3.7 Submodels

Spawning rules: Female salmons aged 4 and above to procreate will get with her nearest male salmon aged 4 or greater. If both salmons belong to the wild population, they will spawn 4 salmons. If the two salmons belong to two different varieties (i.e. either wild or farmed), there is a 60 % spawning chance. If they do spawn, they will spawn 5 hybrid salmons because studies have found that mixed population have a higher spawning success as compared to the wild population (Fleming et al. 2000). If the two salmons are of farmed origin, they have a 60% spawning chance and if they are successful, 3 salmons will be spawned. This is because research has shown that farmed salmon have a lower spawning success as compared to the wild population (Fleming et al. 2000). If the two salmons belong to two different varieties(i.e. either farmed or hybrid), they have a 60 % spawning success and if successful, they will spawn 5 hybrid salmons as studies have found that hybrids have a higher spawning success as compared to the wild population. If both salmons belong to the hybrid population, they have an 80% spawning success rate but if successful, they will hatch 5 hybrids (Fleming et al.). If the male is a hybrid and the female is a wild salmon, there is a 51% spawning success and if successful, 5 hybrids will be spawn. However, if the female is a hybrid but the male belongs to the wild population, there is a 91% spawning rate and if successful, 5 hybrids will be spawn. After successful spawning, the adult salmons die(Fleming et al.). For the new salmons introduced, sex are assigned at random, age is set at 0, color is assigned according to the variety being spawn, and size is set at 3 because we are not modeling size of different variety of salmons. This is also where age is incremented signaling that one year has passed.

Intrusion rules: Every year, escaped farmed salmons enter the environment at the set intrusion rate as a percentage of the current wild salmon population. Their size has been set at 3 because we are not modeling for size and their speed set at 2 body length per sec. They are headed right and their age and sex is randomly assigned.

Surviving rules: For the surviving rule, we have separated the rules by life cycle stage. First we set the egg mortality and young salmons survival chance. Studies have found that hybrids have a higher egg mortality (Hindar et al.). as compared to wild salmons. So hybrid salmons aged less than three years old, have a 30 % chance of not surviving. Mortality for ones are even lower than that of hybrids (Hindar et al.). This has been set at a 20% surviving chance. We then considered salmons at midway of the life cycle and older salmons. Farmed salmons aged 3 have a 12 % chance of dying while wild salmons have a 40 % chance of dying. It has been found that older (here aged above 4) wild salmons have a higher chance of not surviving (Hindar et al.), so there survival rate has been set at 50%. Older farmed female (here aged above 3) have an even lower surviving chance, which has been set at 45%. Farmed salmons aged above 3 have a 35% survival chance because studies have found that older farmed salmons have very low survival chance (Hindar et al.). These probabilities have been set to be coherent with empirical results that several studies have found and match NetLogo's setting.

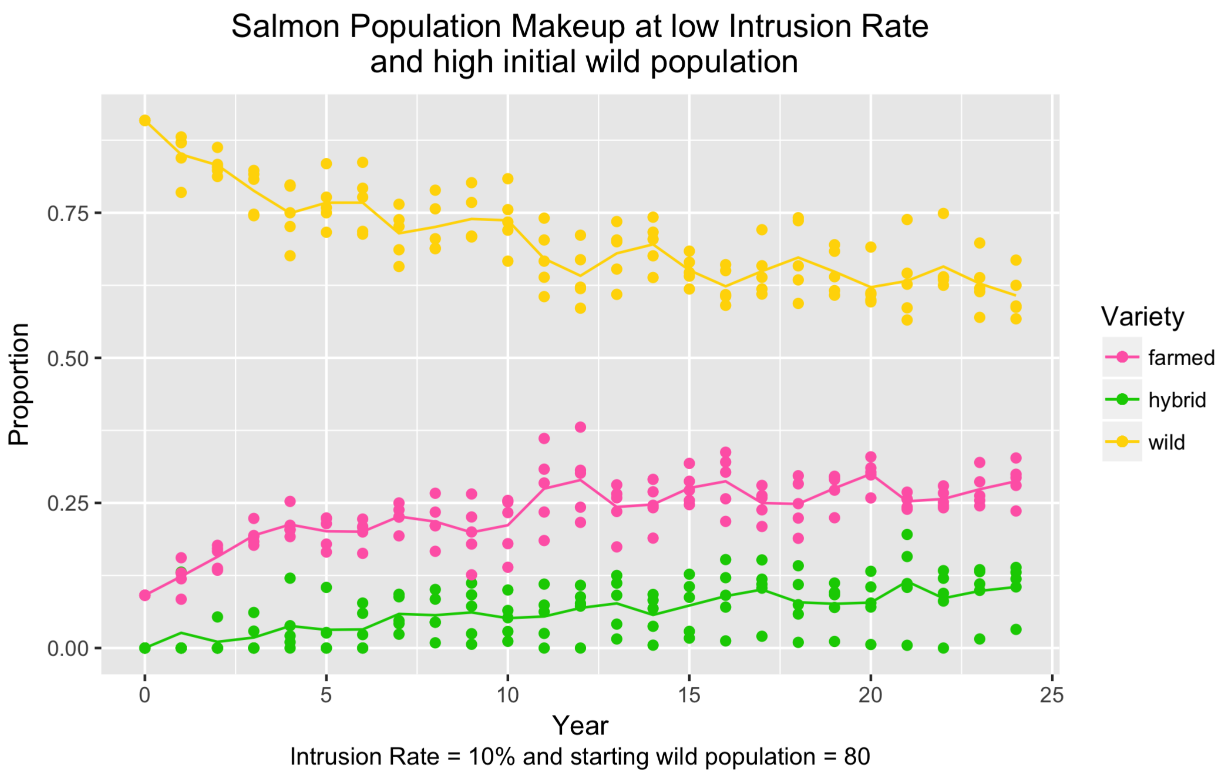
Schooling rules: Schooling rules have been left as programmed by Professor Leise for Math 140 except that r1, r2, r3 have been set at 9.4, 10.6, 35.8 measured in terms of body length respectively. The vision angle has been set at 300 and each salmons pay attention to its 4 neighbors. The escaped salmons enter the environment and follow the schooling rules because escaped salmons join the wild population as they follow the schooling behavior (Hindar et al.).

4 Results

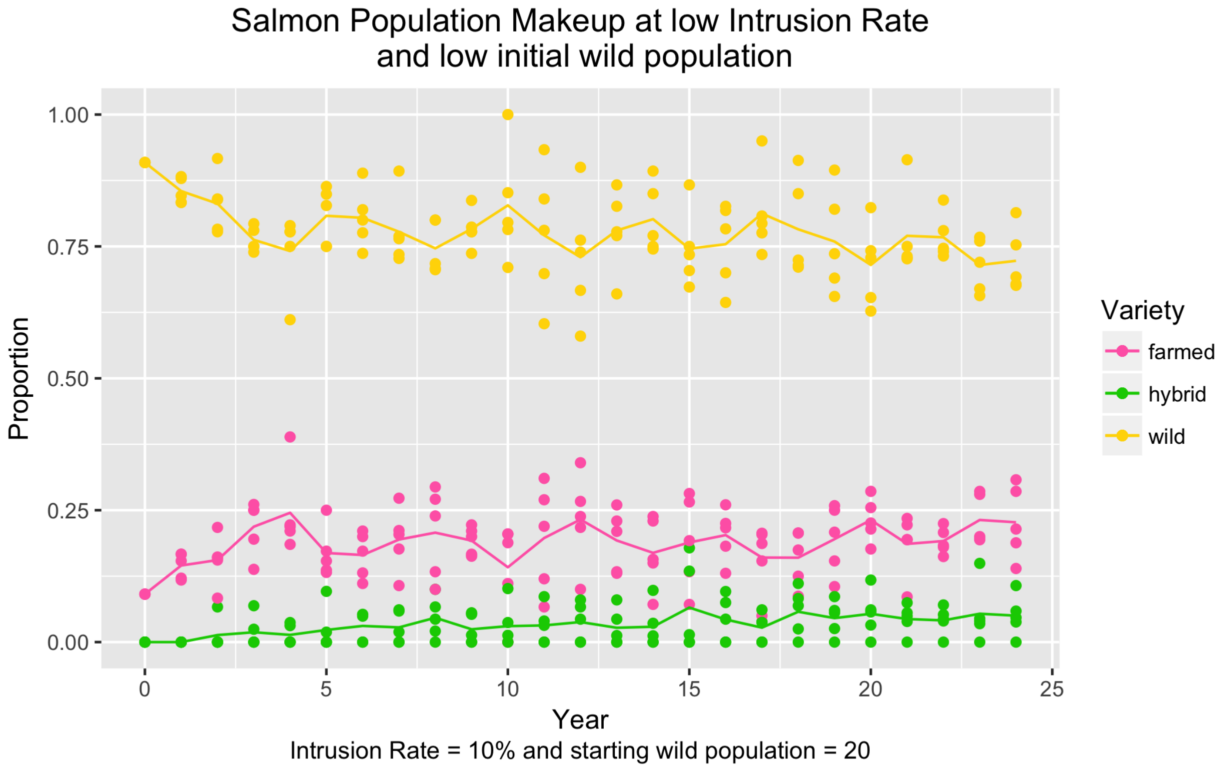
4.1 Population Porportion Makeup

We look look at the population makeup by considering the environment (low/high initial population) and the intrusion rate (low/high). A high intrusion rate is a 50% rate while a low intrusion rate is 10%. A high initial wild population is 80 while a low one is 20 salmons. We ran five simulations over 24 years (four generations) and plotted the results for each year. The lines represent mean proportion for each variety.

4.1.1 low intrusion rate

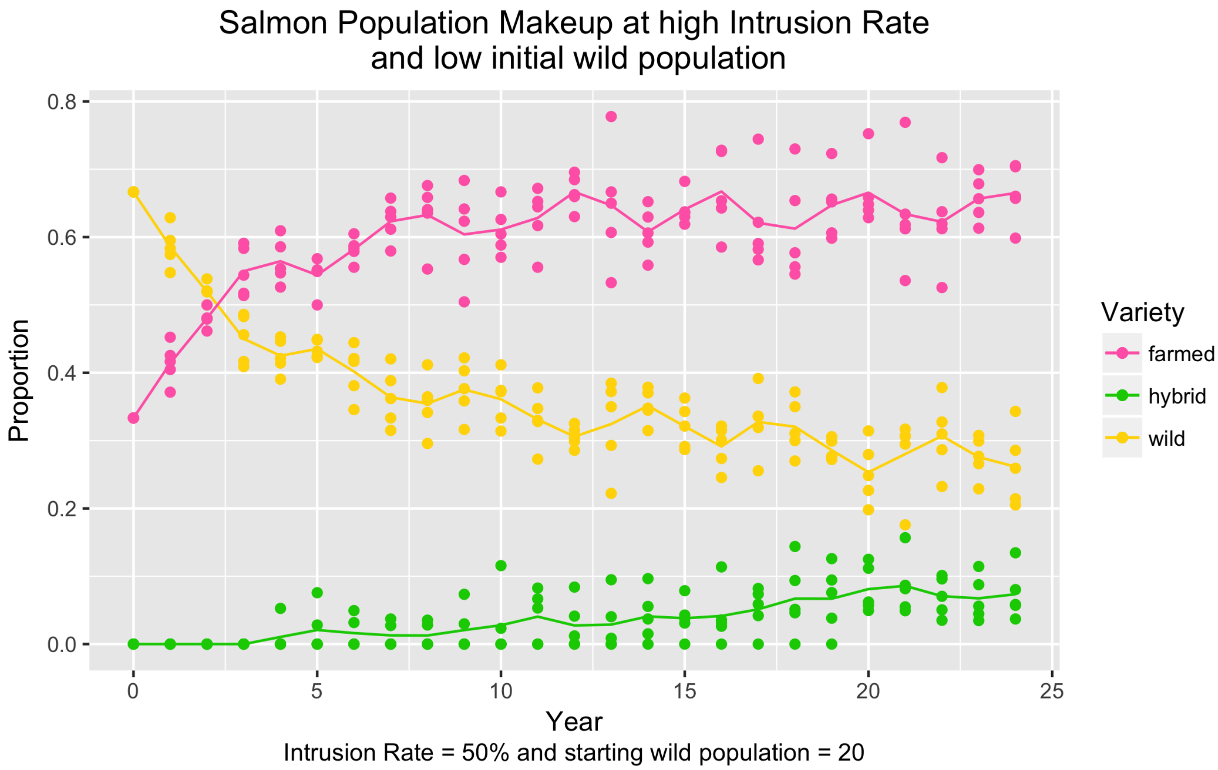


At low intrusion rate and high initial wild population, we see that after four generations, the wild population still dominates even though their proportion falls. There seems to be little interaction between the wild and the farmed salmons and subsequent hybrids because the proportion of hybrids remains lower over the years as compared to farmed and wild ones. Hybrid population seems to be dependent on farmed population as they follow similar trends.

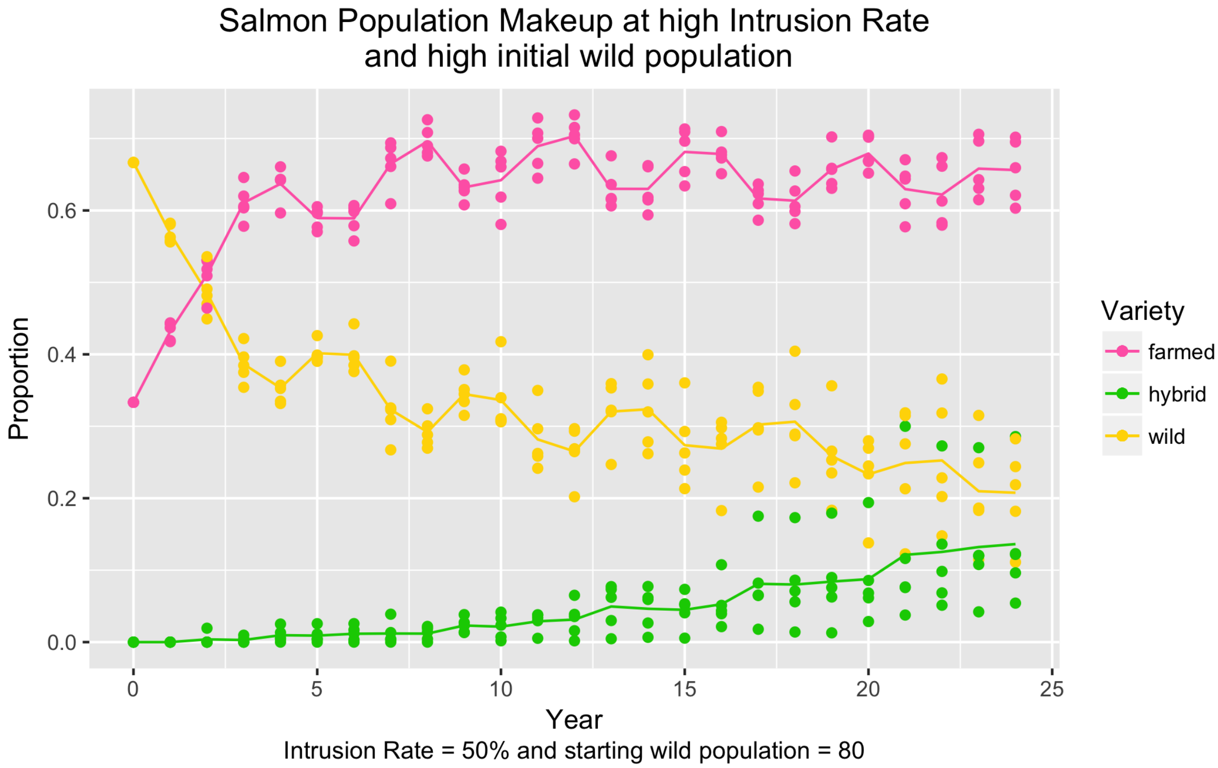


At low intrusion rate and low initial wild population,it is interesting to note that the wild population dominates the population throughout and its mean proportion is more or less constant or rather it smalls at a very samll rate. Farmed salmons remain at a constant proportion and so does the hybrid population which remains at a lower proportion on average as compared to farmed and wild populations. It would thus seem that farmed salmons find it hard to integrate the school.

4.1.2 high intrusion rate



At high intrusion rate and low initial wild population, we see that the wild population as a proportion of total population falls throughout. Farmed salmons overtake the other varieties. There still seems to be little interaction between wild and farmed salmons. The hybrid population grows but does so at a relatively lower rate as compared to the farmed salmons.



At high intrusion rate and high initial wild population, we see that wild population no longer dominates the population and farmed salmons take over. It is only after around three generations that the proportion of hybrids seem to increase at the expense of the wild population. If we extrapolate, it would seem that the hybrid population overtakes the wild population after a few more generations.

4.1.3 Summary of population size and intrusion rate

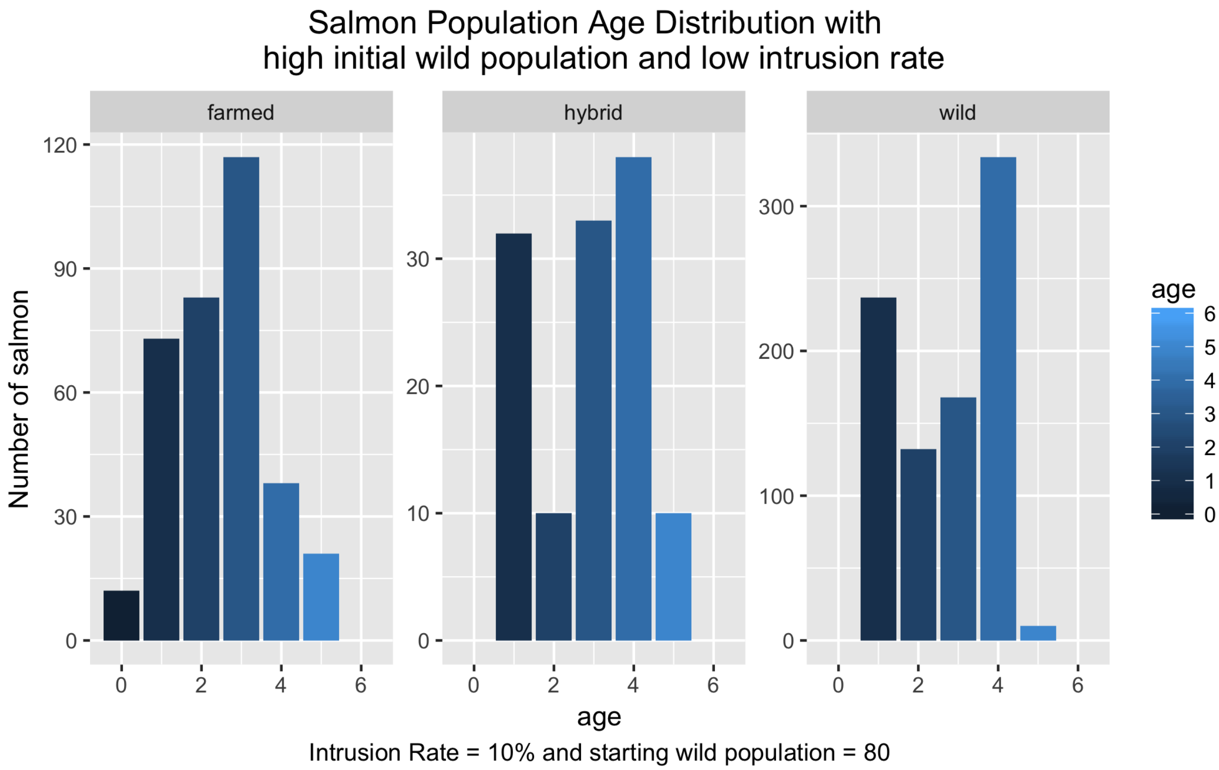
Table 3: Mean Proportion After Four Generations

Variety	High Population and Low Intrusion	Low Population and Low Intrusion	High Population and High Intrusion	Low Population and High Intrusion
Wild	0.61	0.72	0.20	0.26
Hybrid	0.10	0.05	0.14	0.07
Escaped Farmed	0.29	0.23	0.66	0.67

4.2 Variety Age Distribution

We next look at the age distribution for each variety. This would allow us to observe patterns in survival chances. We will look at the age distribution with an initial high wild population of 80 as our environment. We then compare age distribution of each variety at a low intrusion rate(10%) with that of a high intrusion rate(50%). We are looking at the distribution after six generations(i.e. 24 ticks) and we ran five simulations.

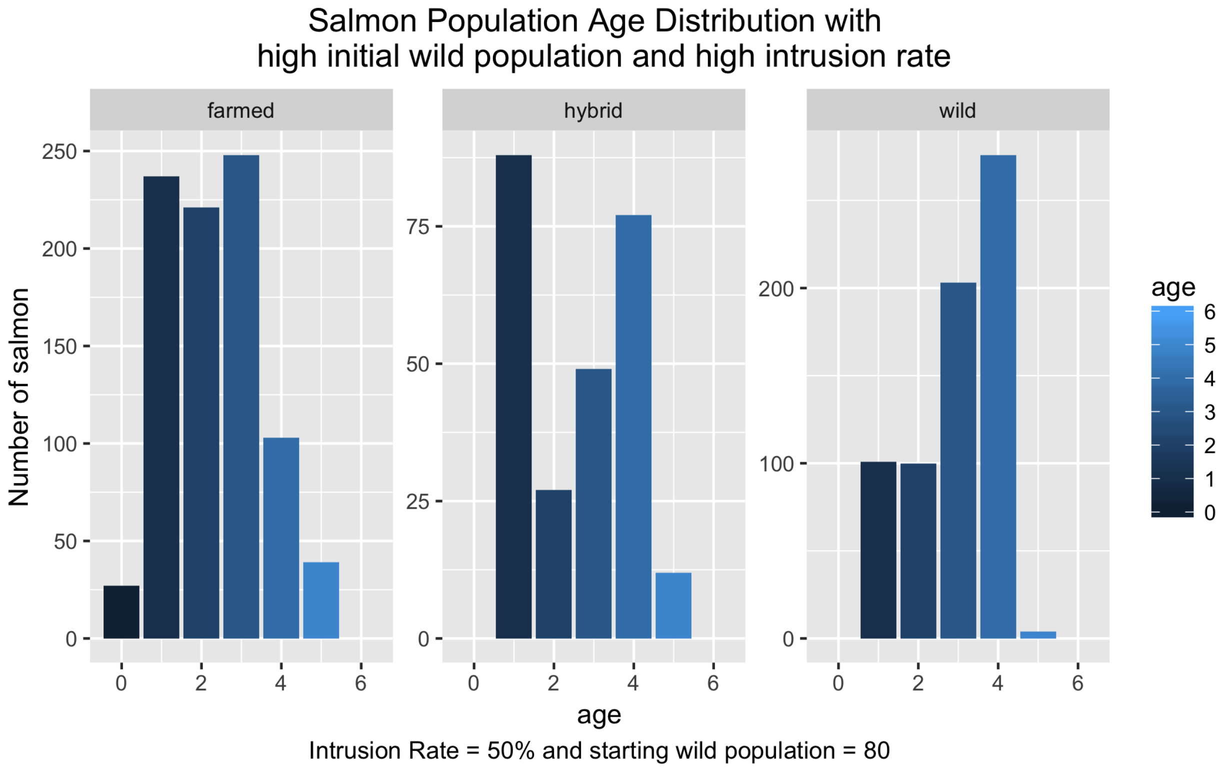
4.2.1 low intrusion rate



At low intrusion rate for escaped farmed salmons we see that, they have low reproduction rates and old salmons (aged 4 and above) have low survival chances. The relatively high number of young and mid life salmons and the normality of the distribution probably stems from the intrusion of recently escaped salmons. Hybrids on the other hand have relatively high reproduction rates but the chance of survival for baby hybrids is quite low relative to the other varieties. Wild salmons seem to fare pretty well like hybrids and most of them reached age 4, there they reach their best reproductive life and that it probably why they die afterwards.

4.2.2 high intrusion rate

At high intrusion rate, the age distribution of escaped farmed salmons is quite normal. This is probably again due to the fact that they enter the population every year. The number of young hybrids seem to be relatively high compared to that of wild but consistent with that of farmed. This high number might stem from the farmed salmons mixing with the wild population and this would account for the low number of young wild salmons. Wild salmons age four is also high and they die soon after so they do get to reproduce but the presence of a high number of farmed salmons, results in a higher probability of producing hybrids. This in turn could explain the low number of young wild salmons.



5 Discussion

The age distribution after four generations with high wild population suggest that at high intrusion rate, the hybrids are likely to be in a larger number and reproduce at a relatively higher rate but the spawning success seems to be relatively small. The results obtained seem to be consistent with the studies by Hindar et al.(2006) and McGinnity et al.(2003). Hindar et al.(2006) modeled over 10 generations while McGinnity et al.(2003) carried out a real-life experiments over two generations. Hindar et al.(2006) found that when the intrusion rate was small, there was a low probability that farmed offspring would dominate the population but found that at high intrusion rate, farmed offsprings and hybrids make up a large proportion of the salmon population. McGinnity et al.(2003) found that the offspring of farmed and hybrid salmons had reduced survival rates as compared to those of wild salmons.

Both studies however, further broke down the varieties while we used a simplified 'wild, hybrid, farmed' version. Hindar et al.(2006) separated the second-generation hybrids, and looked at Backcross to wild and Backcross to farmed as well. They also considered the age of escaped farmed salmons (whether they escaped early or late). McGinnity et al.(2003) also considered the different generation of hybrids and Backcross to wild and Backcross to farmed. The spawning, and survival probabilities as well as the number of spawns were adjusted from empirical results to reflect the size of the population we are modeling. We could also have run more simulations to have a better idea of the spread but five runs seemed to reflect the results sufficiently.

From the results obtained it would seem that at low intrusion rate and low initial population, the wild salmon population is not threatened by escaped farmed salmons and they still dominate the population at high initial population but do so at a lower proportion on average. At high intrusion rate, no matter how big or samll the initial wild population is, the farmed salmons dominate the school. We also had a simple assumption that the intrusion rate was fixed every year. It would be interesting to see what effect a one-time intrusion would have. From our results, we gathered that all hope is not lost in preserving wild population. And there is a possibility that wild and escaped farmed salmons coexist without disturbing the ecosystem. However, the conditions necessary for such a scenario are numerous and controlling for escaped farmed salmons, especially if a fish pen breaks, is hard.

6 Reference

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